Investigating the Relationship between Fin and Blue Whale Locations, Zooplankton Concentrations and Hydrothermal Venting on the Juan de Fuca Ridge

William S. D. Wilcock
School of Oceanography
University of Washington
Box 357940
Seattle, WA 98195-7940
phone: (206) 543-6043 fax: (206) 543-6073 email: wilcock@u.washington.edu

Richard E. Thomson
Department of Fisheries and Oceans
Institute of Ocean Sciences
Sidney, British Columbia V8L 4B2
Canada
phone: (250) 363-6555 fax: (250) 363-6690 email: thomsonr@pac.dfo-mpo.gc.ca

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LONG-TERM GOALS

We are investigating the potential correlation between fin whale tracks, enhanced zooplankton concentrations and hydrothermal vents above the Juan de Fuca Ridge. Our goal is to understand the influences of globally distributed hydrothermal plumes on the trophic ecology of the deep ocean.

OBJECTIVES

We are continuing a study of seismic and bio-acoustical data sets from the Juan de Fuca Ridge with the following three objectives for FY2011 and FY2012:

1. Complete the tracking and detailed analysis of a data set of several hundred thousand fin whale calls recorded on the Endeavour segment over a 3-year period from 2003-2006. Analyze tracks for call characteristics, calling patterns, swimming patterns, net seasonal migration, diurnal variations, interannual variations, correlations with physical oceanography and correlations of call locations and rests and gaps in calling with the location of hydrothermal vents
2. Determine whale call counts for ocean bottom seismometers deployed at mid-plate locations on the Explorer and Juan de Fuca plates and near the continental margin in order to test whether the density of vocalizing fin whales is unusually high around the Endeavour vent fields.
3. Complete the calibration of Acoustic Doppler Current Profiler (ADCP) backscatter intensities in terms of biomass and the analysis of existing ADCP time series, and incorporate high-quality upward looking ADCP data that will be collected by the NEPTUNE Canada observatory. Apply

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the results to understanding the relationship between the seasonal migration patterns of zooplankton and their enhanced concentrations within the water column above the hydrothermal vents.

APPROACH

The W. M. Keck Foundation supported an experiment on the Endeavour segment of the Juan de Fuca Ridge that included a network of eight ocean bottom seismometers (OBSs) that operated from 2003-6. The experiment also included one-year deployments of OBSs on the Explorer plate and the continental slope offshore Nootka Sound (Fig. 1). More recently, NEPTUNE Canada has commenced seismic observations at 4 nodes on their cabled observatory including the Endeavour segment (Fig. 1). The earthquake analysis of the Keck Endeavour data showed that the seismic records include a very extensive data set of fin and, to a lesser extent, blue whale vocalizations. Work on the Juan de Fuca Ridge (McDonald *et al.*, 1995) and elsewhere (Rebull *et al.*, 2006; Dunn and Hernandez, 2009; Frank and Ferris, 2011) has shown that seafloor seismic networks can be used to track fin and blue whales but the data sets have been limited to a few tracks. Our approach is to develop an automatic tracking algorithm (Wilcock, 2011b). Events are identified by triggering on each station using the ratio of short-term to long-term RMS amplitudes and fin whales are distinguished from earthquakes based on their spectra. The times of direct and multiple bounce arrivals are picked based on finding peaks in the instantaneous amplitude of the seismic records. A grid search approach is combined with the ocean acoustical ray-tracing software RAY (Bowlin *et al.*, 1992) to find the location that matches the observed arrival times best. The whale tracks can then be combined with analysis of calling patterns to investigate the behavior of vocalizing whales and their distribution relative to the vent fields.

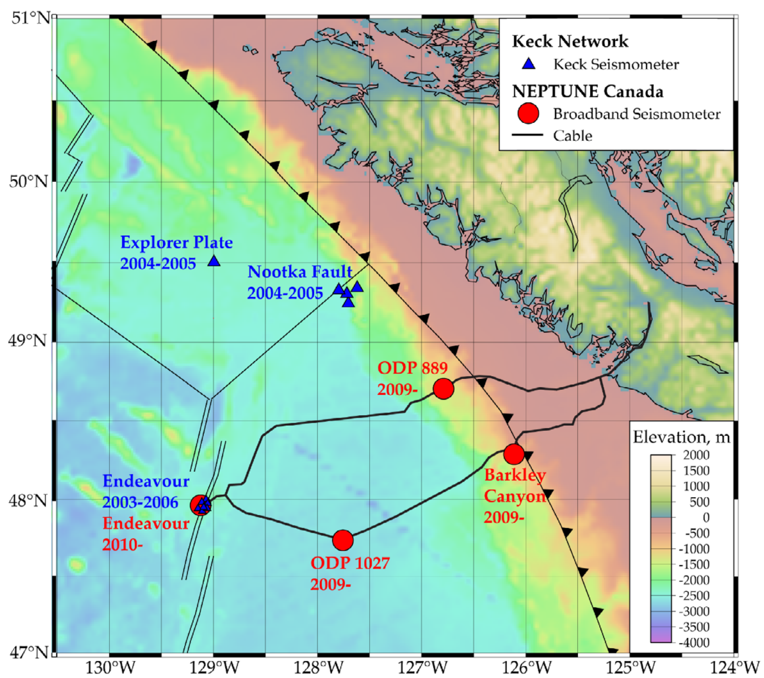

Fig 1. Map of the NE Pacific Ocean off Vancouver Island showing the locations of seismometers deployed in the Keck experiment and broadband seismometers on the NEPTUNE Canada cabled observatory.

In the early to mid-1990s, the Institute of Ocean Sciences in Sidney, BC conducted summer cruises to the Endeavour to collect a series of plankton net tows in conjunction with measurements including acoustic backscatter intensity. The prior analysis of net samples collected in 1991-4 shows enhanced zooplankton concentrations at all depths above the hydrothermal vent fields (Burd and Thomson, 1994; 1995). At depth, the zooplankton are concentrated in a layer of increased acoustic backscatter near the top of the hydrothermal plume (Thomson *et al.*, 1991; Burd *et al.*, 1992), leading to the inference that the zooplankton are grazing on the plumes. Community analysis shows that the deep faunal assemblages above the vents are infiltrated by shallow species which presumably migrate vertically between the upper ocean and the hydrothermal plume (Burd and Thomson, 1994; 1995). Our approach is to analyze additional net samples collected in the area from 1995-6 to identify major zooplankton and fish species and determine length, gender, stage of development, and dry/wet biomass. The expanded zooplankton data set can be used to refine our understanding of variations in zooplankton concentrations with distance from the hydrothermal vent fields. The data on zooplankton distribution and biomass in the water column overlying Endeavour Ridge are well suited to acoustic calibration of net samples because the ADCP was mounted just below the multiple-net apparatus and the attitude sensors and current measuring capabilities of the ADCP allowed us to determine the flow volume with only 2 to 3% error (Burd and Thomson, 1993). A close regressional relationship between the biomass and acoustic backscatter (for the specified scattering cross-sectional model) means that profile acoustic data can be used to map three-dimensional distributions of biomass in the vicinity of the ridge without the need for expensive and labor intensive net sampling tows. The relationship can be used to interpret upward looking ADCP data collected in the Axial Valley with autonomous instruments deployed from 2003-6 and with the NEPTUNE Canada cabled observatory starting in 2010.

WORK COMPLETED

1. *Whale Tracking.* In the previous reporting periods, we developed an automatic arrival time picking and locating algorithm for fin whales (Wilcock *et al.*, 2009), investigated the incorporation of additional constraints from amplitude and particle motions, and demonstrated the use of a cross-correlation and double difference method (Waldhauser and Ellsworth, 2000) to refine tracks. Graduate student Dax Soule obtained ~100 tracks for 2003-4 (Soule *et al.*, 2009) and developed a supervised spectrogram-based method to analyze the fin whale calling patterns along the tracks. In this year we have added some additional refinements to improve the reliability of the tracking, presented the double-difference method at the 5th DCL workshop (Wilcock, 2011a) and submitted a manuscript describing the tracking algorithm to the *Journal of the Acoustical Society of America* (Wilcock, 2011b). We have extended our data set of tracks for 2003-2004 from ~100 to >150 and have completed the analysis for call characteristics, calling patterns, swimming patterns, net seasonal migration, diurnal variations and correlations of call locations and rests and gaps in calling with the location of hydrothermal vents. UW graduate student Dax Soule has prepared a manuscript describing the results which will be reviewed by his M.Sc. committee this fall prior to submission to *JASA*.

2. *Whale Call Densities.* First-year UW graduate student, Michelle Weirathmueller has evaluated two automated methods to detect fin calls, the first based on applying matched filters in the time domain and the second based on cross-correlating a time-frequency model of a fin whale call with a data spectrogram (Weirathmueller *et al.*, 2011). Call counts normalized to a uniform background noise level have been determined for the Endeavour, Nootka and Explorer plate sites. Preliminary call counts have also been determined for the NEPTUNE Canada sites. The conversion of call

counts at single stations to call densities is dependent on the distance at which the fin whales can be detected. This is influenced by the call source levels and by the effects of water depth and seafloor lithology and roughness on the amplitudes of water column multiples. We have initiated work to measure the source levels for calls located close to seismic stations and model the effects of differing seafloor characteristics on the amplitudes of multiples.

3. *Net Sample and ADCP analysis.* In previous reporting periods, we analyzed 30 net samples collected in 1995 for species, gender, age, and net biomass (wet and dry weight) and processed all the acoustic backscatter, water property, and flow velocity data collected during towed ADCP/CTD/Optics/Tucker trawl surveys near Endeavour Ridge in 1995-6 to add to the 1991-4 historical database. We also examined acoustic backscatter time series collected from 2003-6 by upward looking ADCPs moored at several sites within the axial valley. We used simultaneous acoustic backscatter and net tow data from 1991-4 to obtain a preliminary calibration of the acoustic observations. This year, we completed the analysis of net samples collected in 1996 and processed data from a total of 29 combined shipboard ADCP-net biomass tows conducted near Endeavour Ridge over the period 1991 through 1996. These data have been used to prepare an invited article to be published in the Oceanographic Society journal *Oceanography* (Burd and Thomson, 2011) that examines biological productivity in the vicinity of the hydrothermal venting areas of the ridge. Progress on the analysis of the NEPTUNE Canada ADCP data has been slowed by logistical problems encountered by the NEPTUNE Canada cabled observatory. We had hoped to have a total of four upward-looking 75 kHz ADCP systems working within the Axial Valley of Endeavour Ridge by this time. Unfortunately, NC has only been able to deploy two of the four systems to date. The first system (RCM-NE) was deployed to the northeast of the High Rise vent field in September 2010; the second system (RCM-NW) was not deployed to the northwest of High Rise until the end of September 2011. As a consequence, work during the present reporting period has been confined to the current, temperature, salinity, and acoustic backscatter time series from the NE mooring.

RESULTS

Whale Tracks. We have analyzed the calling patterns of 155 tracks with durations ranging from ~1 hour to nearly 24 hours by identifying the times and frequencies of fin whale calls from a modified spectrogram. The tracks can be classified into 4 categories based on the inter pulse interval (IPI): (1) simple 25 s IPI tracks, (2) 25/30 s dual IPI tracks, (3) 13/25 s dual IPI tracks and (4) complex IPI tracks in which the IPI ranges from <5 s to ~30 s and shows no clear pattern. With the exception of some of the complex tracks, all the tracks include rests (IPIs > 70 s) whose characteristics vary for track to track from a quite regular spacing and duration to a very irregular pattern.

The 25/30 s dual IPI tracks are the most common representing ~50% of the tracks (Fig. 2). These together with the simple 25 s IPI tracks (~20% of the tracks) appear to be produced by a single whale and comprise calls with a center frequency of 20 Hz together with 18 Hz 'backbeat' calls (Hatch, 2004; Hatch and Clark, 2004) that occur more frequently as the trailing call of the 30 s IPI and as the first call following rests. These tracks are sometimes relatively straight (e.g., Fig 2) but often meander slowly through the experiment region. The 13/25 s dual IPI tracks are the least common in our data set (~10% of the track) and often include two distinct frequencies; a 20 Hz call and a higher frequency 25 Hz call that occurs at the end of the 13 s IPI. We interpret these tracks as resulting from two whales responding to one another. The complex IPI tracks (~20% of the tracks) are typically composed of

multiple frequencies (six in one instance) and tend to be relatively straight tracks that move across the experiment area in a few hours. We interpret these as the result of pods of transiting whales.

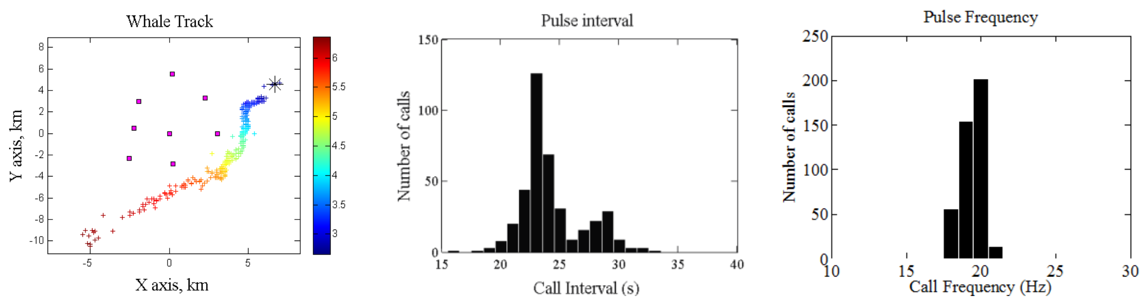

Fig 2. (Left) Example of a dual 25/30 IPI track for February 4, 2004. The network is shown by purple boxes and the track by crosses color coded by time of day. Over 4 hours the whale swims from east of the network to the southwest. (Center) Histogram of pulse interval showing peaks near 25 s and 30 s. (Right) Histogram of call frequency showing a peak near 20 Hz.

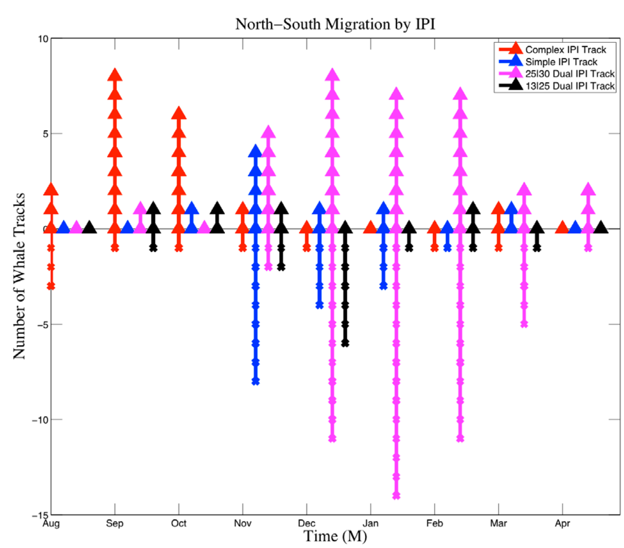

Fig 3. Distribution of tracks types by month with tracks moving form north to south plotted on the positive Y-axis and track moving from south to north plotted on the negative axis. Complex IPI tracks occur predominantly in the fall and move northwards while the simple and dual IPI tracks are predominantly in the winter and have a slight tendency to move southward.

Fig. 3 shows the distribution of tracks by month and their net direction. From August to October the complex IPI tracks are the most common and these are predominantly directed northward. The simple IPI tracks are the most common track in November, the dual 25/30 s IPI tracks dominate from

November to March and the 13/25 s dual IPI tracks are most common in December. These tracks all have a weaker tendency to be oriented southwards. Although our dataset only covers a very small area the net directionality is inconsistent with the commonly observed pattern of baleen whale migration in which whales head north in the spring and south in the fall (e.g., Payne and Webb, 1971; Mizroch *et al.*, 2009). The complex IPI tracks that include many higher frequency calls may be pods of juvenile males that are headed north in the fall. The simple and dual IPI calling patterns are generally attributed to breeding males (Watkins *et al.*, 1987; Croll *et al.*, 2002) and show a much less pronounced tendency to meander slightly southward over the winter.

The overall spatial distribution of tracks (Fig. 4) does not show a very clear tendency for vocalizing whales to be concentrated above the hydrothermal vent fields on the mid-ocean ridge as might be expected if the vocalizing whales were feeding on zooplankton above the hydrothermal plumes. The distribution appears far from random with highest concentrations to the east of the network and lowest to the southwest. Since it is not generally believed that vocalizing whales are feeding (Watkins *et al.*, 1987), these results do not disprove the hypothesis that the fin whales are taking advantage of the enhanced zooplankton concentrations found near the mid-ocean ridge. The apparent non-random distribution of the tracks suggests that there are local influences on the distribution of fin whales but their origins are unclear. Tracks form years 2 and 3 may yield additional insights and will allow us to obtain robust maps of track densities for the different IPI categories.

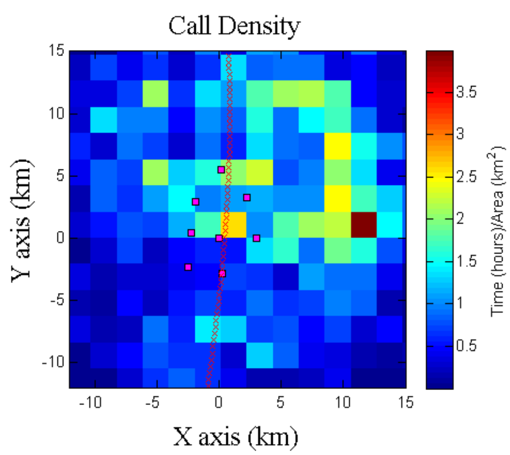

Fig 4. Density of calling whales in units of hours per kilometer squared. The highest densities are observed to the east and within the network and the lowest to the southwest.

Whale Call Densities. Our evaluation of automatic fin whale detection algorithms shows that both the time domain matched filter and spectrogram cross-correlation methods work well with the matched filter performing slightly better (Weirathmueller *et al.*, 2011). Fig. 5 shows histograms of call counts that have been adjusted to account for different background noise levels for 2004-5 from the Endeavour, Explorer Plate and Nootka Fault sites (Fig.1). The call count is lower at the Endeavour than the other two sites but without further analysis we cannot be certain that this is not an artifact of enhanced propagation of seafloor multiples at the Explorer and Nootka sites resulting from the smooth sedimented seafloor. Interestingly the call count while low everywhere is higher at the Endeavour from April to June when the bottom mounted ADCP data suggests early stage zooplankton offspring

migrate from above the hydrothermal plumes towards the surface before growing rapidly in the upper ocean waters. The preliminary histograms of call counts over the winter of 2010-11 for the four NEPTUNE Canada seismometer sites show quite complex temporal patterns that vary from site to site. We are in the early stages of searching for correlations with oceanographic parameters such as surface temperature, mixed layer depth and chlorophyll concentrations (Stafford *et al.*, 2009) in order to understand what might be causing these variations.

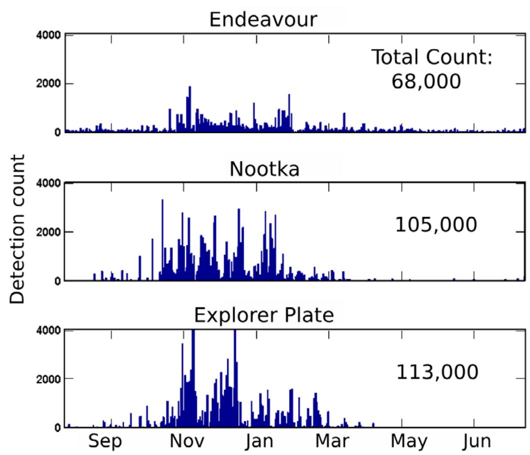

Fig 5. Histograms of daily fin whale call counts for the Endeavour, Nootka and Explorer plate sites for 2004-5. The detections have been normalized to a uniform background noise level. Detections are highest between November and March at each site and the total number at the Explore and Nootka sites is almost double that at the Endeavour.

ADCP and Net Tow analysis. The analysis of the combined shipboard ADCP-net biomass tows data (Burd and Thomson, 2011) suggests that productivity is influenced by downward organic fluxes from marine production in the surface ocean as well as upward organic fluxes from vent plumes on the seafloor. The vent material is also distributed throughout the water column by deep migrating and reproducing zooplankton. Because logistical challenges, time, and cost of towed net surveys make it difficult to conduct studies of secondary biomass and production in the water column of the open ocean, profiling acoustic backscatter instrumentation (such as the ADCP used in our work) provide an operationally more straightforward and less time consuming approach to investigating zooplankton biomass in the ocean. Linking these two approaches has been problematic in the past because the collection of net samples and acoustic backscatter data has typically not been undertaken simultaneously from the same volume of water. Using a modified fluid-sphere model and highly accurate flow volume measurements for the nets, we find that the acoustic backscatter signal accounts for 82% of the variance in the net biomass data (Fig 6). Results are unaffected by organism size, daily migratory patterns, or depth range. Burd and Thomson (2011) discuss the potential use and limitations of this approach in broad-scale, full water-column studies of secondary production in the vicinity of the Endeavour Ridge vent region.

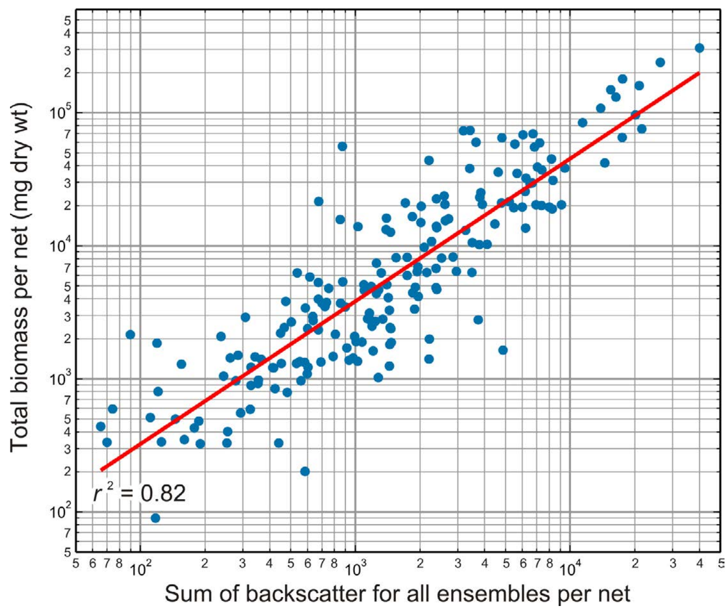

Fig 6. Log-log scale linear regression of total net biomass versus sum of target strength over all acoustic ensembles based on a fluid sphere model (Burd and Thomson, 2011). The regression predicts 82% of the variance in the data.

The year-long data series from the paired single-point Nortek acoustic current meters and Seabird CTDs (positioned over the depth range 5 to 200 m above bottom), and the single Teledyne-RDI 75kHz ADCP (looking upwards from 250 m above bottom at the top of the mooring), is very gappy due to problems with the cable interface systems. Although processing these time series has been labor intensive, we have a sufficiently complete record to examine seasonal changes in acoustic/biomass variability and higher frequency variability in the deep to mid-water productivity using data segments within the overall time series. This work is in progress.

IMPACT/APPLICATIONS

We have developed automatic fin whale detection and tracking algorithms that can be applied to other seafloor seismic networks. The location method could be applied to other vocalizing species (or anthropogenic sounds) with a network of seafloor receivers provided the calls are sufficiently short and spaced far enough apart so that the direct and multiple arrivals do not overlap. The close relationship between biomass and acoustic backscatter provides a method to extrapolate limited net tow data to images of the 3-D distribution of biomass. If a correlation if found between the distribution of whales, enhanced zooplankton concentrations and hydrothermal vents it will have implications for our understanding of the global influences of hydrothermal vents on the trophic ecology of the ocean (Gisiner *et al.*, 2009).

RELATED PROJECTS

The Endeavour node on the NEPTUNE Canada regional cabled observatory is steadily being populated by water column experiments that will monitor deep macrozooplankton concentrations

(Rick Thomson is the lead-PI) and by a seafloor seismic network (William Wilcock is a co-PI). The amphibious portion of Cascadia Initiative is an ambitious NSF project that will deploy 70 OBSs at ~140 sites for 2 years each over the Juan de Fuca plate and Cascadia margin from approximately 40°N to 50°N, thus providing the opportunity to investigate the broader spatial and temporal distribution of fin and blue whales.

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Burd, B. J., and Thomson, R. E. (**2011**). "Estimation of zooplankton biomass at Endeavour Ridge using an acoustic Doppler current profiler (ADCP) calibrated against concurrently towed nets," Oceanography, submitted.

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